Investigation of Sulfur Concrete Mixes for Mars Infrastructure

by

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Abstract

Space is a vast and enticing place known as the final frontier. As the world progresses through time, it becomes more interested in the frontier of space. Much research is conducted on different facets of life in space, and this research project's intent is to make habitats on Mars more plausible. By creating a Martian soil simulant using commercially available materials and then comparing how that simulant performs in a series of tests that another Martian soil simulant was put through, this project would find if it was able to create and utilize an accurate facsimile of Martian soil. The Martian soil simulant facsimile was combined with sulfur in this project to create a sulfur concrete that was then placed through testing to determine the compression strength of the created sulfur concrete. The sulfur and Martian soil simulant concrete is then recast and tested again to determine the strength gain. This process is similar to a project that utilized a Martian soil simulant that was contracted by NASA for use in Martian research. The results of this project were compared to the results of that project, and it was observed that the strength of the sulfur concrete that utilized the Martian soil simulant made from commercially available materials failed under lower compressive loads. One possible reason for this is that the facsimile did not contain all the oxides present in the original Martian soil simulant, due in part to lack of accessibility of the materials and budgetary limitations. This result meant that this project's Martian soil simulant had a lower compressive strength in a sulfur concrete mixture than that of a sulfur concrete that utilized a control Martian soil simulant. The Martian soil simulant created in this research

did not produce statistically significant similar results of a NASA contracted Martian soil simulant due to the research deviations that are noted within this document.

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Introduction

When you think of space, what comes to mind? At first it might be astronauts or the moon, but undoubtedly the planet Mars will make its way into your thoughts. The fourth planet from the sun has been featured in movies, tv series, and science fiction novels of all kinds. Beyond that, multiple theories have been written on many of its features and its past, and numerous tests and studies have been done on the planet, most of which are conducted by NASA. For over a hundred years the mysterious “Red Planet” has fascinated writers and scientists alike, and this paper is a result of yet another person being drawn in by the planet’s mysteries and possibilities.

Although it is not the closest celestial body to our planet, it is the most likely candidate for humanity’s next step in space exploration. The moon, the closest celestial body to Earth, lacks anything close to a substantial atmosphere and is thus an unsuitable option for humans to live on for an extended period of time without extreme protection. Venus, the next closest celestial body to Earth, is also unsuitable for human life. It has an atmosphere that is 92 times more massive than Earth’s (Hammer, 2017, p. 2), and its mass is the primary reason that surface temperatures on Venus can reach nearly 500°C (Hammer, 2017, p. 2). Humans would either be crushed by the mass of Venus’ atmosphere or burn up due to the surface temperatures.

Mars, however, has an atmosphere that can protect humans from radiation and its temperature averages at -63°C (Williams, 2018), much more suitable for humans than either Venus or the Moon. With these facts, I believe that Mars is the best qualified celestial body for human settlement, which may not be as far off as some people believe.

NASA is already moving towards that goal, and they intend to put astronauts on Mars as early as the 2030's (Wilson 2017), with multiple unmanned missions being conducted before that. NASA also recently held a competition that invited teams to design 3D printable habitats for further space exploration (Harbaugh, 2019).

While we can see that Mars is the best candidate for human settlement, and that at least one organization is moving steadily towards that goal, there are still numerous problems that pose a threat to humanity's journey to the Red Planet. Chief among these is the issue of habitats for humans to live in, as well as the materials for these habitats. We can see that NASA is addressing the design of the habitats, but when I first began this project, my interest was piqued at finding the possible material to build the habitats. Being a Concrete Industry Management major, my first thought was the possible use of concrete. I quickly discovered the folly of this idea, however.

Concrete is a compound of cement, water, and aggregates (commonly known as rock and sand). When concrete forms, the liquid water reacts with the cement in a process called hydration. When this reaction is finished, the mixture hardens, and the result is what we call concrete. However, there are multiple problems with using concrete on Mars. The most prevalent problem is that the atmospheric pressure on Mars is only around 6.0 mbar (0.0592 atm), as opposed to Earth's pressure of 1014 mbar (1.0074 atm) (Williams, 2018) and is not high enough for H_2O to exist in its liquid state. It can only exist either as a vapor or as a solid, ice. This means that the hydration reaction is impossible, as the liquid water required for it cannot exist in the Martian atmosphere. Even if it were possible for H_2O to exist in a liquid state on Mars, water is a limited commodity there, and would be greatly expended if it was used in building materials. Aside from water, the Portland cement required for the mix would have to be shipped from Earth, as the minerals required to create it are decidedly rare on Mars.

With concrete no longer an option, more literature research was done to try to find a possible construction material to use on Mars, with the additional stipulation that the materials had to be found in some level of abundance on Mars itself. This was to limit the amount of construction materials that would need to be brought from Earth, as the cost of sending materials into space is quite pricey. Even using the most efficient rocket currently available, the Falcon Heavy rocket, it would still cost $90 million dollars to send a 16,800-kilogram payload to Mars, which comes out to roughly $5,357 per kilogram (Cobb, 2019). A small tiny house weighs 1100 kilograms which would mean the cost to ship the required elements of standard living would be over $6 million for one home.

In the course of this literature search, Northwestern University's work quickly became the prevalent source. They proposed using a sulfur-based concrete to construct Martian habitats using *In Situ* resources. Using hot-melted sulfur as a form of bonding agent is not a new idea, in fact it is known to have been used in prehistoric times (Sheppard, 1975). Even though it is not a new idea, using sulfur as the bonding agent in a concrete is specifically ingenious for use on Mars. In reference to using resources found on the planet, there has been convincing evidence provided by the Viking, MER, and Pathfinder rovers that surficial deposits on Mars are enriched in Sulfur (McLennan & Grotzinger, 2008), and a lower-limit estimate calculates that there is enough sulfur in the sedimentary layer that if Mars were covered in a soil layer with 6% SO_3 content it would be 2km thick (McLennan & Grotzinger, 2009).

Sulfur is also well suited for use in the Martian environment. While concrete cannot form due to the interaction of Mars' atmosphere and water, sulfur can freely melt into a liquid and cool into a solid in the Martian atmosphere and temperature ranges (see Figure 1). This means that aggregate can be added to the melted sulfur and remain there as it cools, forming a solid, sulfur concrete. Sulfur has a low melting point which is part of what makes it efficient as a bonding agent. However, this can also cause issues with sulfur melting in high temps, which is a legitimate danger when it is used on Earth. Mars temperatures are ≤35°C, which is far below sulfur's melting point of 120°C.

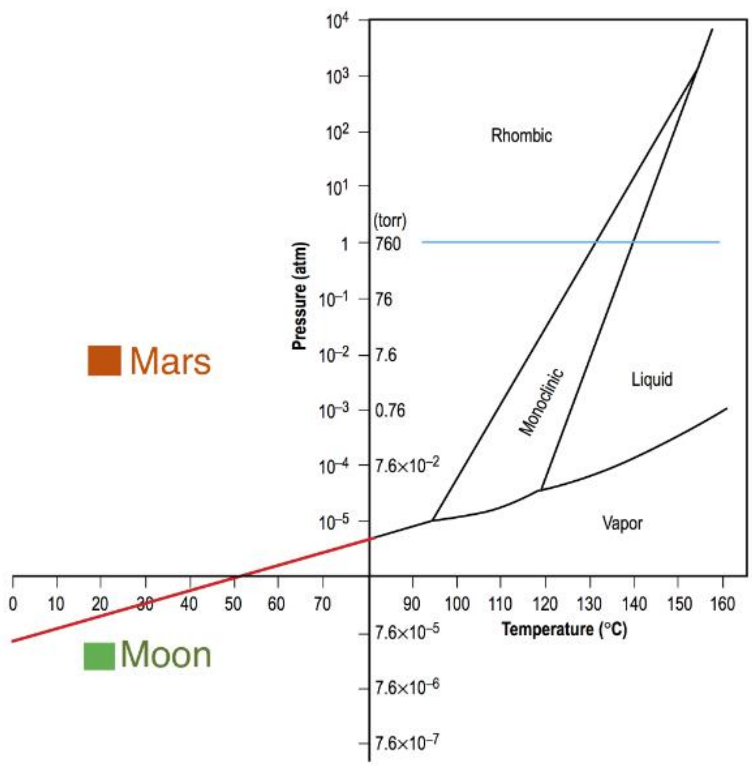


Figure 1: Sulfur Phase Diagram (Grugel, 2008)

To continue the efficiency of using *In Situ* resources, Northwestern University decided to use a Martian soil simulant (Wan, Wendner, & Cusatis, 2016, p. 7) to simulate a sulfur concrete that was made with 100% Mars materials. The Martian soil simulant they used was called JSC Mars-1A (Orbital Technologies Corporation, 2008) which NASA contracted the Orbital Technologies Corporation to create. The simulant's chemical makeup was based on readings taken by the Viking and Pathfinder probes at their landing sites (Allen et al., 1998, p. 1).

With this knowledge, the thesis research pursued the route of acquiring an amount of the JSC Mars-1A soil simulant so that a simulation of Northwestern University's research could be performed and taken to the nest step of iterative mixes. Northwestern conducted mechanical tests on the sulfur concrete they created, therefore the research focused on finding ways to improve upon their mixing, pouring, and curing processes so that the strength of the sulfur concrete could be improved. These strength results could then be calculated for various types of structures suitable when using sulfur concrete on Mars.

These plans were re-routed, however, when it was discovered that soil simulant JSC Mars-1A is no longer produced or sold. The next step determined was to seek a company that could combine the major elemental components of JSC Mars-1A (see Table 1) and thus recreate the simulant. This endeavor was unsuccessful as a company was not willing to re-create the formula noted by Northwestern. Moving forward, it was decided that the oxides from Table 1 should be ordered and used to simply recreate the Martian soil simulant in the MTSU lab. The recreated simulant would then be used to conduct tests similar to those done by Northwestern University in their research article. These results will be compared to those of Northwestern University's tests to see how accurate the recreated soil simulant is and whether materials are available to conduct such research and ultimately advance the mission of creating available mixtures for Martian construction.

Table 1: Major Elemental Components of Soil Simulant JSC Mars-1A (Orbital Technologies Corporation, 2008)

Major Element Composition	% by Wt.
Silicon Dioxide (SiO_2)	34.5-44
Titanium Dioxide (TiO_2)	3-4
Aluminum Oxide (Al_2O_3)	18.5-23.5
Ferric Oxide (Fe_2O_3)	9-12
Iron Oxide (FeO)	2.5-3.5
Magnesium Oxide (MgO)	2.5-3.5
Calcium Oxide (CaO)	5-6
Sodium Oxide (Na2O)	2-2.5
Potassium Oxide (K_2O)	0.5-0.6
Manganese Oxide (MnO)	0.2-0.3
Diphosphorus Pentoxide (P_2O_5)	0.7-0.9

Materials and Methods

Equipment:

- Scientific Scale, accurate to one-hundredth of a gram.
- Steel Cube Mold
- Sulfur Heating Pot
- Instron Satec 500 kip Compression Machine
- Table Saw

- Heat Resistant Cup

ASTM Standards:

- C109/C109M-16a – Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)
- C192/C192M-18 – Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory

In order to find the most appropriate oxides for use in this project, the oxides were only purchased from companies that were trusted to provide quality testing materials, such as Sigma-Aldrich. Due to budgetary limitations and lack of availability, some of the oxides that made up Martian soil simulant JSC Mars-1A were left out of the mix, which may or may not have played a significant role as a variable in the results of the research project. The oxides that were not included were diphosphorous pentoxide, potassium oxide, sodium oxide, and iron oxide.

The oxides that were excluded made up between 5.7% and 7.5% by weight of JSC Mars-1A. The aforementioned percentage range may not be a large portion of the soil simulant, but it is not known how significantly each of the oxides effect the end product, and thus the exclusion of the four oxides could have an effect on the results of this project.

To calculate the amount of each remaining oxide to combine to make a facsimile of JSC Mars-1A, the maximum percent was taken from the range of each one on table 1 and added together. The resulting percentage from this was 93.3%, which left 6.7%

remaining. This remaining percent was multiplied by the percentage of each of the oxides and that amount was added to each one, resulting in a weighted distribution of the extra percentage (refer to Table 2).

Northwestern University's article was used to determine the ratio of recreated soil simulant to sulfur. The article showed that the most efficient ratio, the one that provided the highest strength, was 50% sulfur to 50% soil simulant (Wan, Wendner, & Cusatis, 2016, p. 8). This was the percentage chosen for this research project as well.

For the first batch of tests, two cube forms were needed, and to fill these as well as have extra material to account for any material loss in the process, a mix of 900 grams was designed. This meant that the mass of the recreated soil simulant would equal 450g, and the amount of each oxide was calculated proportionally (refer to Table 2). The sulfur used in the mixture would equivalently be 450g.

Each oxide was measured out on a scale that was accurate to one-hundredth of a gram and placed directly into the inactive heating pot. This direct transference was done to avoid excessive material loss in transit. An excess of 0.03-0.10g was still allowed in each oxide to compensate for whatever small amounts of material were potentially lost in transit. Figure 2 shows a picture of JSC Mars-1A (a) next to a picture of the recreated simulant for comparison of color. The 450g of soil simulant and the 450g of sulfur powder were combined in the sulfur heating pot and homogenized.

Table 2: Oxide Percentages and Mass Amounts in Recreated Martian Soil Simulant

Material	**Original %**	**End %**	**Size (g)**
SiO_2	44%	47%	211.5g
TiO_2	4%	4.3%	19.35g
Al_2O_3	23.5%	25.1%	112.95g
Fe_2O_3	12%	12.9%	58.05g
MgO	3.5%	3.8%	17.1g
CaO	6%	6.5%	29.25g
MnO	0.3%	0.4%	1.8g


(a)


(b)

Firgure 2: JSC Mars-1A (a) (Orbtec., n.d.) and recreated Martian soil simulant (b)

The sulfur heating pot was then covered and turned on to a temperature of ~280°F, a comfortable 40°F hotter than the melting point of sulfur. The pot was checked three hours after it was turned on and the mixture was found to be in a semi-solid state. In practicing beforehand with a sulfur capping compound, the mixture had melted after roughly an hour of heating, so this seemed to be much slower than just sulfur alone. After ensuring that none of the other oxides in the mix would melt if the temperature was increased and that it wouldn't adversely effect the sulfur itself, the temperature in the pot was increased to 320°F under the assumption that the sulfur was simply not being heated efficiently enough. Two and a half hours later the mixture was checked again and found to still be in a semi-solid state (see Figure 3).

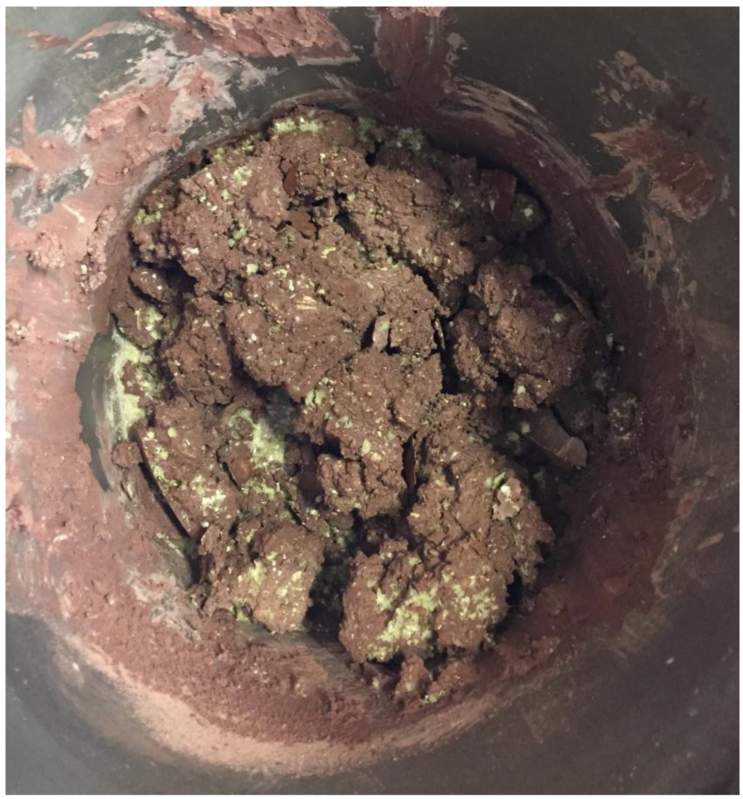


Figure 3: 50/50 Sulfur-soil simulant mixture after 1 ½ hours of heating.

The hypothesis as to why this happened relates to the size of the individual particles of the oxides used in this research as opposed to those used by Northewestern

University. In Northwestern's tests, they reduced the size of the particles of JSC Mars-1A to a maximum of 1mm, which indicates that there would be many particles at or near the 1mm mark (Wan, Wendner, & Cusatis, 2016, p. 7). The oxides used in this research, by comparison, had an overall size of roughly half of 1mm or smaller. This would mean that the recreated soil simulant would have a higher surface area than JSC Mars-1A and would therefore require a higher amount of bonding agent to produce enough free bonding material between particles to enter into a liquid state.

It was decided to increase the sulfur in the mix to the point that it equaled 60% of the material by weight. The reason this was decided was that Northwestern University ran tests with 60% sulfur mixtures as well, so there would still be results to compare against. To bring the percentage of sulfur up to 60%, 225 grams of sulfur was added to the mixture in the pot and heating was resumed. The adition of the sulfur produced the desired consitency in the mix, as shown in Figure 4.

Figure 4: Recreated soil simulant and sulfur (60%).

Before this process was begun, a test run was performed using a sulfur capping compound and the forms that would be used. In this practice run, it was discovered that cold joints would be a risk (shown in Figure 5). A cold joint occurs when two layers of a material are placed at even slightly different times and the two layers cool at different temperatures. Mass contracts as it cools, and because the two layers are cooling at different temperatures, one layer contracts before the other, causing a joint to appear. In an attempt to prevent this, the forms were placed as close as possible to the heating pot to reduce the transfer distance and therefore the time period between placing layers. Due to the diameter of the heating pot and the volume required to fill the forms, it was not possible to transfer enough material in one load to completely fill the forms.

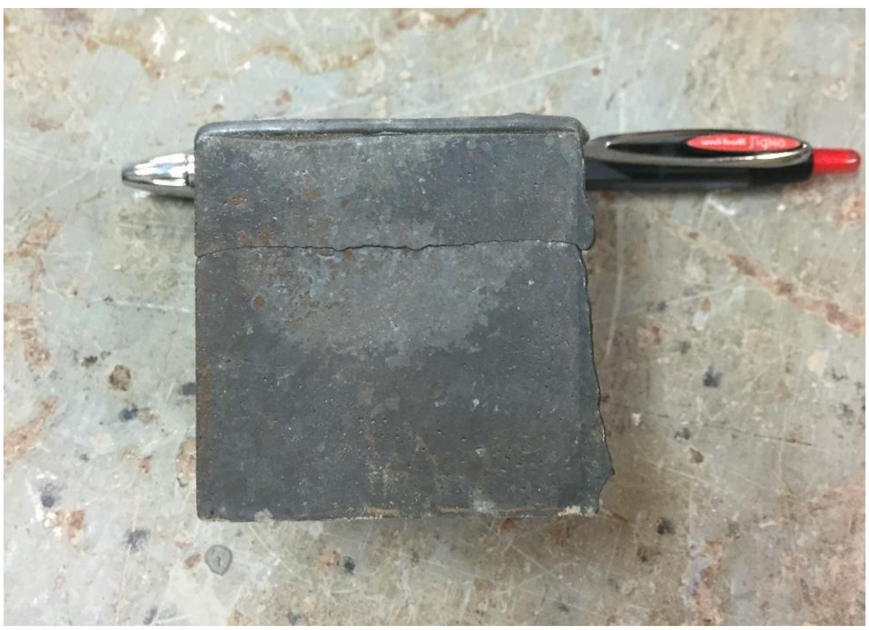


Figure 5: Cold joint shown in a practice cube made of sulfur capping compound.

In addition to reducing the risk of cold joints, measures were also taken to prevent a large differential in cooling between the center of the material in the forms and the the material along the inside edge of the forms. To reduce this risk, the forms were placed inside an oven at 150°F (±25°F) so that the metal of the forms would not act as a significant heat sink (a material that transfers heat from one medium to another). In Northwestern's research, an unquantified but well distributred level of pressure was applied to the forms when they placed the sulfur concrete (Wan, Wendner, & Cusatis, 2016, p. 9). For this research project, the forms were placed on a vibration table that was turned to a low setting, providing a source of compaction.

Unfotunately, shortly after the sulfur concrete mixture was placed in the forms, a considerbale subsidence of material was observed in the middle of the cube forms (Figure 6). Extra material was placed on top of the first placement of material to bring the level of material back above the edge of the forms. This of course produced an unavoidable cold joint that could potentially have played a role in the results of the research, which will be discussed in more detail in the conclusions section.

Figure 6: Center subsidence of sulfur concrete in cube forms.

After the sulfur concrete was poured, it was left alone for 24 hours to replicate the process of Northwestern University as well as to allow the sulfur of the mix to completely change into orthorhombic sulfur, which is the stable form of sulfur at standard temperatures (Wan, Wendner, & Cusatis, 2016, p. 3). After the 24 hours were complete, the sulfur concrete cubes were removed from the forms. As you can see in Figure 8, both cubes a & b featured small cracks, possibly caused by shrinkage as they cooled. One of the cubes (b) could have gone through a more thorough compaction, as it shows more visible voids than that of Northwestern University's specimen, c.

To prepare the sulfur concrete cubes for testing, the edges along the top of each one were cut off with a table saw to provide a smooth surface for unconfined compression testing. Each example was then placed in the Instron compression machine (Figure 7) and run through an unconfined compression test. There was some difficulty in getting the tests started, as the machine kept would not seat a pre-load which can produce a false negative of a completed test.

Figure 7: Sufur concrete cube in the Instron Satec compression machine.

The reason for this is that the compression machine slowly compresses the specimens until it measures a sudden drop in resistance from the specimen it is compressing, as it is programmed to believe that that is a sign of compressional failure. However, due to the larger number of voids in a sulfur concrete example as opposed to a normal concrete sample, many of the voids inside the sulfur concrete cube were compressed before the cube itself was, causing miniscule cracks and the machine measured these as a specimen failure. To counteract this issue, a load of roughly 250-500psi was preloaded onto the specimens before the procedure was begun.

 (a)  (b)

 (c)

Figure 8: Sulfur concrete cubes after removal from forms, 1A (a) and 1B (b), shown in comparison to a sulfur cube from Northwestern University's research (c) (Wan, Wendner, & Cusatis, 2016, p. 9).

The physical results of the unconfined compression tests are shown in Figure 9. The cubes did not break in a similar fashion, although the compression strength of each was similar to one another (discussed more in results section). The next step of the process was to gather all of the material used in the first round of testing and place it back into the heating pot. This was to melt and recast the sulfur-soil simulant mixture, a procedure that Northwestern conducted in their research. Northwestern University's research showed that when the mixture is recast its strength improves (Wan, Wendner, &

Cusatis, 2016, p. 8), which is the hypothesis under which this section of the project was conducted.

 (a)  (b)

 (c)

Figure 9: Break pattern of sulfur concrete cubes 1A (a) and 1B (b) and the recast sulfur cube (c).

The reheated mixture was placed into the forms in much the same manner as the original batch of sulfur concrete with a few exceptions. Rather than just preheating the forms, the scooping utensils were also preheated, and the forms were preheated at a higher temperature of 200°F. As the material was placed in the form, an extra mount was intentionally piled up on the top-center to compensate for the previously observed subsidence. The cube was then allowed to sit for roughly 42 hours before removal from the forms (due to inability to conduct research due to classes and availability of the lab). The recast cube was then run through an unconfined compression test, with a break pattern shown in Figure 9 (c).

Results:

As stated in the methodology section, the results from the unconfined compression test for cubes 1A and 1B were similar, with 1A breaking at 1178.25 psi and 1B breaking at 1128.75 psi. Results that close together are favorable, as they indicate that the sulfur and Martian soil simulant mixture was homogeneous. It also shows that the methods used to place and compact the material in the forms were similar and similarly executed. Unfortunately, these numbers are a far cry from those of Northwestern University's tests. As shown in Figure 10, Northwestern's test for a 60% sulfur mix (Mars1A 1mm) resulted in a strength of 45-46 MPa, which is equal to 6526-6672 psi. Thus, the sulfur concrete cubes used in this project, utilizing the recreated Martian soil simulant, reached approximately 16.9-18% of the strength of the cubes formed by Northwestern University.

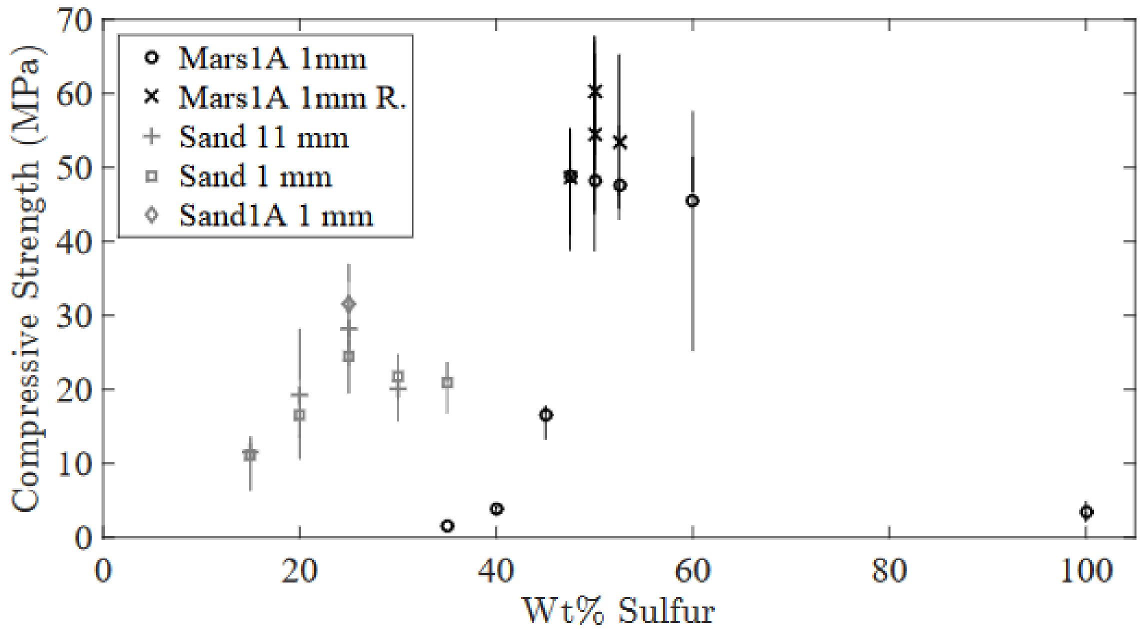


Figure 10: Compressional strength of Northwestern University's research (Wan, Wendner, & Cusatis, 2016, p. 10).

The recast cube was cast and tested under the hypothesis that it would follow the trend of Northwestern University's research. In other words, it was expected to break under a heavier load than that of the original sulfur concrete cubes. This hypothesis was proven when the recast cube broke at 2547 psi. The compressional strength of the recast cube cannot be directly compared to any results from Northwestern University's research because they only conducted recast tests with 50% sulfur and 50% soil simulant mixtures, not 60% sulfur mixtures.

However, we can compare the strength that is gained from recasting the mixture. In Northwestern's research, recasting the sulfur concrete resulted in a 20-30% strength gain for their 50% sulfur mix (Wan, Wendner, & Cusatis, 2016, p. 8). In this research project, recasting the sulfur concrete resulted in a 216-225% strength increase.

Summary and Conclusions:

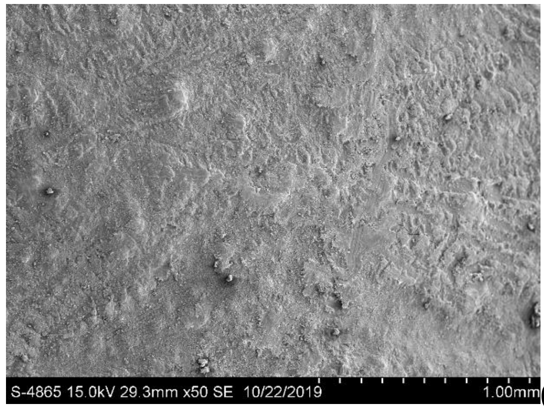
The hypothesis of this research was that it was possible to recreate Martian soil simulant JSC Mars-1A in a relatively cost affordable way so that students and professors from other universities could run tests using a facsimile of Martian soil simulant JSC Mars-1A. The accuracy of the facsimile created in this project would be tested by using it in the same fashion as Northwestern University. If the results of this research had matched up closely with those of Northwestern's research, then this project would have been successful in that endeavor and the facsimile could have been used by other collegiate members for their own research.

The recreated simulant was mixed with sulfur to create a sulfur concrete, and then it was run through unconfined compression tests to find if its strength was similar to that of the mixture used in Northwestern's research. As shown above, the strength of the sulfur concrete cubes using the recreated soil simulant only reached a fraction of the strength of sulfur concrete cubes using the actual JSC Mars-1A.

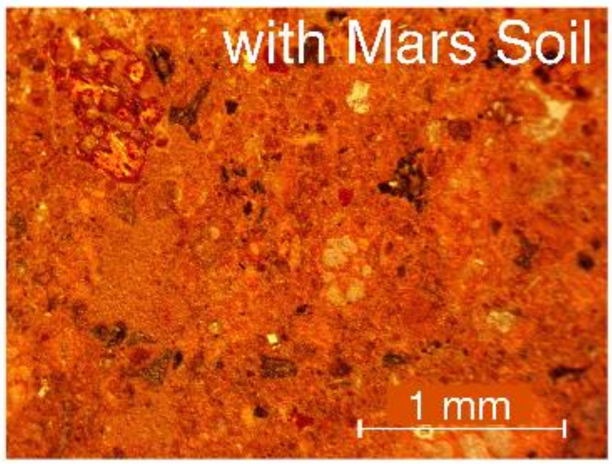
There are several factors that may have played a part in the lower strength of the sulfur concrete made in this project. The first factor is that the recreated Martian soil simulant did not contain every oxide present in JSC Mars-1A due to monetary restrictions and the lack of availability of material. The oxides that were excluded were diphosphorous pentoxide, potassium oxide, sodium oxide, and iron oxide.

In Northwestern University's paper, they state that the particle size distribution of the soil simulant plays a significant role in the material strength of the sulfur concrete. The evidence they provide is that the sulfur concrete they tested that used sand as its aggregate showed a 29% strength gain when its particle size distribution was matched to that of the sulfur concrete utilizing JSC Mars-1A as its aggregate (Wan, Wendner, & Cusatis, 2016, p. 9). Due to the fact that the materials used in this research project were already sized smaller than 1mm, the particle size distribution of the recreated soil simulant could not be changed to match that of Northwestern University's, and this could have played a role in the decreased compressional strength of the sulfur concrete cubes.

The presence of yellow sulfur nodules, as seen in Figure 9, could be a sign that the mixture was not entirely homogenized in the sulfur heating pot. Rather than being completely dispersed throughout the entire mix, the localized nodules of sulfur could have produced weak spots thereby weakening the overall cube as well. When microscopy pictures taken of the sulfur concrete made in this project are compared to those taken by Northwestern University in their project, it becomes apparent that this project's mixture is not as well graded as that of Northwestern University's (Figure 11). Large particles are visible on the surface, which are potentially the sulfur nodules mentioned above. These particles are considerably larger than the size of the particles set into the surface.



(a)



(b)

Figure 11: Microscopy pictures of the sulfur concrete created in this project (a) and the sulfur concrete created by Northwestern University (b) (Wan, Wendner, & Cusatis, 2016, p. 12), resized to match the scales.

On the structural side, the compaction method used in this project, a vibration table, may have been different from the method used by Northwestern University, and it may also have been inadequate, resulting in an excess of voids that then decrease the strength of the sulfur concrete. Supporting this theory was the presence of a central void in both of the original sulfur concrete cubes. You can see this void in one of the cubes in Figure 12. Due to it's break pattern, the void in the second cube is not easily visible.

Figure 12: Central void in sulfur concrete cube 1A.

When the original cubes were placed in the forms, an extra amount of material was added on the top to compensate for a subsidence. This act undoubtedly produced a cold joint in the cubes, which is another factor that could have lowered the compressional strength of the sulfur concrete. As well as affecting the strength of the original sulfur concrete cubes, the cold joint could also have played a role in the significantly high strength increase of the recast sulfur concrete. As the subsidence was specifically prevented in the recast sulfur concrete cube, there was not a cold joint present in that cube, and thus did not have the potential to detract from the recast sulfur concrete's strength.

Certain variables could have been responsible for why the recast sulfur concrete in this project was over 200% stronger than the original sulfur concrete, as opposed to the lower 20-30% strength gain that was expected. In Northwestern University's research, they only conducted recast strength tests on sulfur concrete mixtures of 50% sulfur (Wan, Wendner, & Cusatis, 2016, p. 8), whereas a sulfur concrete mixture of 60% sulfur was tested in this project. This could result in a higher percentage of strength gain if sulfur is the reason that recasting increases the strength. For example, if the sulfur in the mixture is specifically what gains higher strength due to the recast process, then having a higher percentage of sulfur in a mixture would result in a higher percentage of strength gain.

While the hypothesis of this project was not proven beneficial to re-creating a soil simulant for additional mix iterations, there are several potential directions in which it could be expanded or redirected. One of the issues with the sulfur concrete in this project was the speed at which it set (solidified) once it was removed from the sulfur heating pot. This fast setting makes it difficult to compact the sulfur concrete as well as increasing the risk of cracks as it cools. If the mixture was placed into a constantly heated form, perhaps by placing it on a stove eye, and the heat was incrementally stepped down, then perhaps the volume of voids would be reduced, as well as reducing the risk of cracks.

As final analysis was being done for this project, it was discovered that another Martian soil simulant had been produced and was being sold by the Center for Lunar and Asteroid Surface Science (CLASS Exolith Lab, n.d.). This simulant, MGS-1, is supposed to be the first mineralogically accurate Martian simulant (Cannon, 2019), and no research was found that had used this simulant in a sulfur concrete testing procedure. As it is said to be the first Martian soil simulant that is mineralogically accurate, it would undoubtedly be beneficial to see how it would react when used in a sulfur concrete mixture. This would likely provide a more accurate simulation for using building materials from Mars. This would be a new direction for this research project building upon the lessons learned in mixing, casting and testing.

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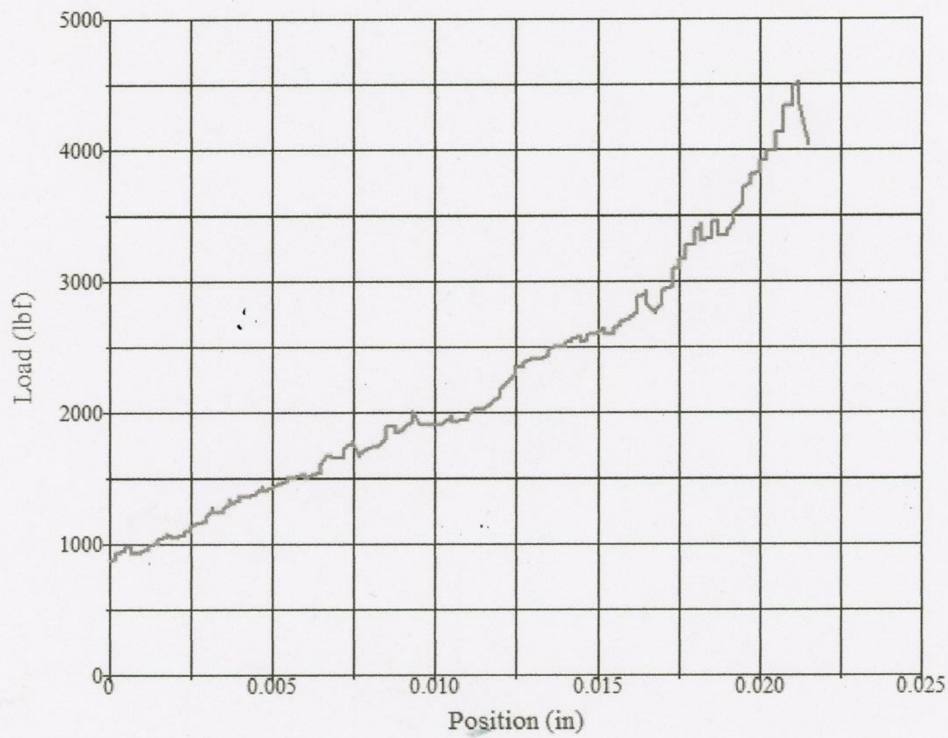
Appendix: Compression Test Results

Sulfur Concrete Cube 1A

HPUSER-HP7556 1:49:29 PM 10/9/2019



Test Summary

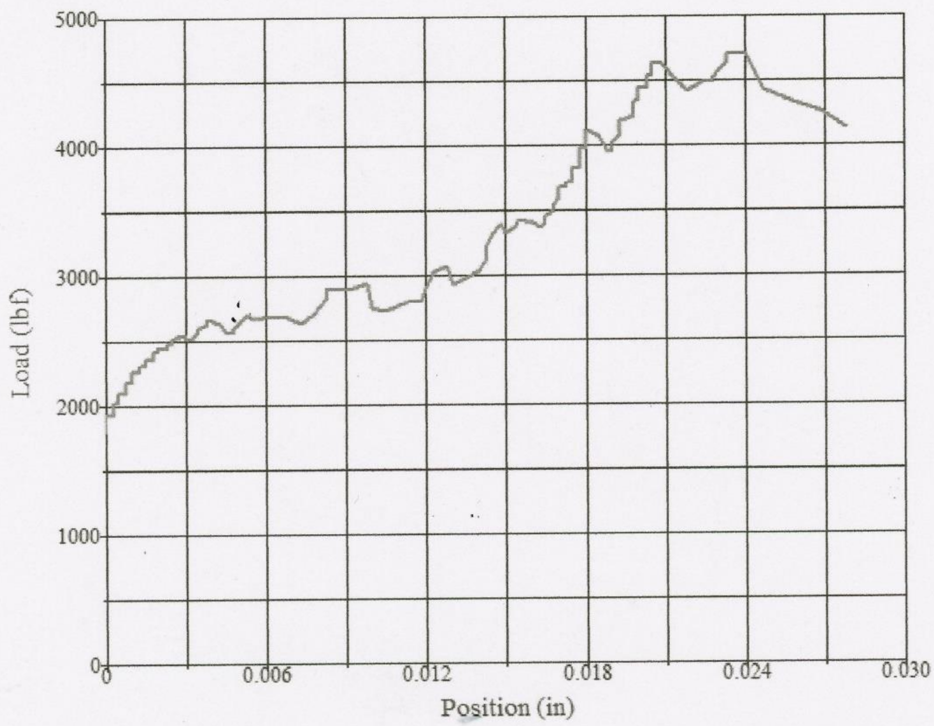
Counter:	7556
Elapsed Time:	00:00:26
Procedure Name:	Cube
Start Date:	10/9/2019
Start Time:	1:48:33 PM
End Date:	10/9/2019
End Time:	1:48:59 PM
Workstation:	HPUSER-HP
Tested By:	Default
Customer:	
Operator:	
Specimen Identification:	Sulfur Cube 1B
Student:	

Test Results

Side Length:	2.0000 in
Area:	4.0000 in²
Compressive Strength:	1128.7500 psi

Sulfur Concrete Cube 1B

HPUSER-HP7555 1:38:09 PM 10/9/2019



Test Summary

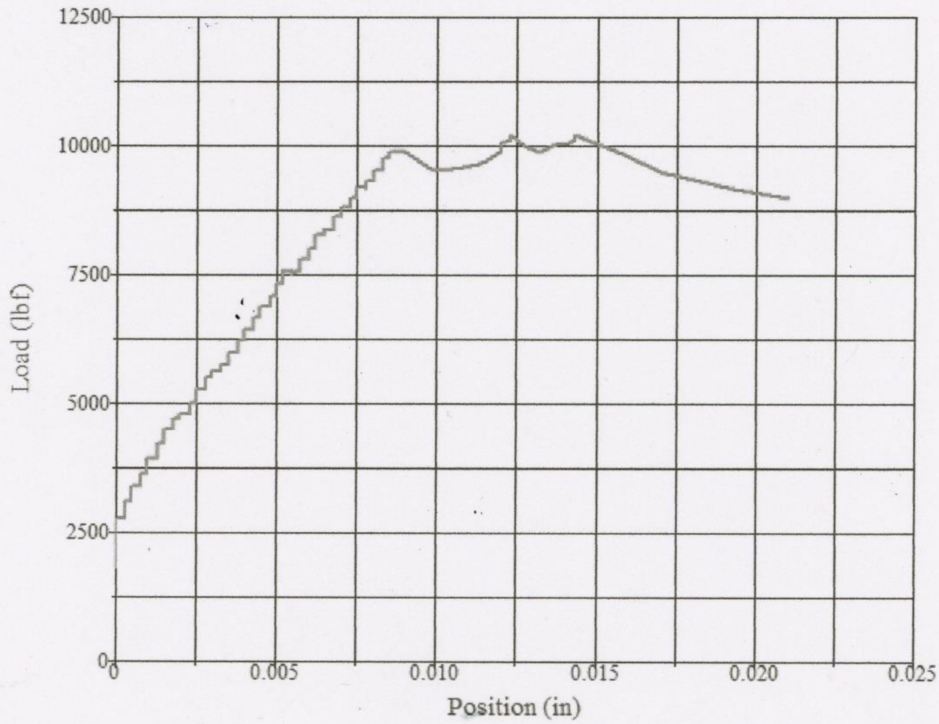
Counter:	7555
Elapsed Time:	00:00:23
Procedure Name:	Cube
Start Date:	10/9/2019
Start Time:	1:37:06 PM
End Date:	10/9/2019
End Time:	1:37:29 PM
Workstation:	HPUSER-HP
Tested By:	Default
Customer:	
Operator:	
Specimen Identification:	Sulfur Cube 1 A
Student:	

Test Results

Side Length:	2.0000 in
Area:	4.0000 in^2
Compressive Strength:	1178.2500 psi

Recast Sulfur Concrete Cube

HPUSER-HP7578 8:08:06 AM 10/17/2019



Test Summary

Counter:	7578
Elapsed Time:	00:01:00
Procedure Name:	Cube
Start Date:	10/17/2019
Start Time:	8:06:58 AM
End Date:	10/17/2019
End Time:	8:07:58 AM
Workstation:	HPUSER-HP
Tested By:	Default
Customer:	
Operator:	
Specimen Identification:	Recast Cube A
Student:	

Test Results

Side Length:	2.0000 in
Area:	4.0000 in²
Compressive Strength:	2547.0000 psi